https://doi.org/10.31705/BPRM.v4(1).2024.15

Emerging Small Modular Nuclear Power Reactors

Small Modular Reactors (SMRs) are advanced nuclear reactors with a typical electrical output up to 300 MWe per unit and can produce 7.2 GWh per day, which is about one-third of the capacity of traditional nuclear power reactors. There is an emerging interest on SMRs and their applications among many nuclear power member countries as a potentially viable nuclear option since it is an environmentally friendly carbon free solution to contribute in mitigating the climate change.

SMR reactors are designed as a single or multimodule plant incorporating advanced safety features to minimize potential accident risks. They are under deployment for all principal reactor technology types such as water-cooled reactors, high temperature gas-cooled reactors, liquid metal-cooled fast neutron spectrum reactors, molten salt reactors, and microreactors (capacity <10 MWe). The main factors driving the development of SMRs include the demand for flexible power generation for diverse users and applications, the need to replace ageing fossil-fuel units, upgrading the safety performance, and enhanced economic affordability.

SMRs are designed for niche electricity or energy markets where large reactors are impractical. They have the potential to offer cogeneration for heat, hydrogen production, and desalination, making them suitable for small electricity grids, remote or off-grid areas, and in hybrid nuclear-renewables energy systems. Hybrid nuclear-renewables energy systems are integrated facilities that combine nuclear reactors, renewable energy generation, and industrial processes. They are designed to meet the demands for grid flexibility, reduce greenhouse gas emissions, and optimize the use of capital investment [1].

SMRs are modular type reactors, since the components and systems can be shop fabricated and then transported to the sites for installation as demand arises. Hence SMRs aim to achieve economies of serial production, leading to shorter installation and construction times. Near-term deployment SMRs are anticipated to offer safety performance on par with or exceeding that of current evolutionary reactor designs. The modular design and advanced safety features of SMRs make them attractive in industries and countries with smaller grid sizes and limited nuclear expertise. Some transportable turnkey systems are being developed, built entirely in shipyard factories, and then delivered to remote locations or exported as marine plants. These systems are designed for plug-and-play installation, providing both electricity and heat.

SMRs produce less electricity than traditional nuclear power plants with electricity generating capacities between 700 and 1400 MWe. However, SMRs require significantly less land—about 7 hectares compared to the 259 hectares needed for a traditional reactor plant. The compact and modular design of SMRs offers substantial economic benefits. An SMR can be constructed in a factory in about 3 to 5 years, with costs ranging from $1 to $3 billion USD. In contrast, building a traditional nuclear power plant takes between 6 to 12 years and costs between $6 to $12 billion USD. The economic competitiveness of SMRs compared to large reactors is a significant topic within the scientific community [2]. Beyond size, factors such as co-siting economies, modularization, construction time, and other aspects must be considered. Operating and decommissioning costs are also crucial. Early studies have suggested that SMRs might have a higher Levelized Cost of Electricity (LCOE) compared to traditional nuclear plants [3]. However, this cost tends to decrease with large-scale serial production. To advance SMR development, the industry needs a standardized, holistic approach to evaluate the economic and financial competitiveness of SMRs.

SMRs feature simpler designs that incorporate passive safety systems, which rely on natural physical processes, such as gravity and natural heat convection, to shut down and maintain reactor cooling in the event of an incident. Unlike traditional plants that use active safety systems requiring electrical signals and human intervention, SMRs' passive systems ensure that cooling continues even if power is lost. This reduces the risk of human error and enhances safety.

Additionally, the smaller size of SMRs means they use less nuclear fuel compared to traditional reactors. Light water-based SMRs could use low-enriched uranium, similar to traditional nuclear power plants, with enrichment levels around 5% U-235. Another option for future SMRs is high-assay low-enriched uranium (HALEU), which ranges from 5% to 20% U-235. Additionally, light water SMR cores can be designed to use plutonium as mixed oxide (MOX) fuel. SMRs with non-light water reactor coolants may be even more effective at managing plutonium and minimizing waste disposal requirements [4].

A conventional 1000 MWe nuclear plant typically requires about 27 tons of uranium annually. The fuel requirements and associated waste for SMRs are scaled down in proportion to their capacity compared to traditional reactors. SMRs offer various fuel handling options and generally require less frequent refueling—every 3 to 7 years, as opposed to 1 to 2 years for conventional plants. Some SMRs are designed with fuel that lasts 10 to 12 years, eliminating the need for onboard used fuel storage. These SMRs can be fabricated and fueled in a factory, then sealed and transported to sites for power generation or processing heat. At the end of their lifecycle, they are returned to the factory for defueling, reducing the need for transportation and handling of nuclear materials.

One of the key challenges for nuclear power plants remains the scarcity of U-235. A potential solution to the challenges of nuclear fuel scarcity is the use of a mixture of Thorium and Transuranic (TRU) elements. Thorium is significantly more abundant than Uranium, with enough estimated reserves to support nuclear power for thousands of years. Integrating Thorium with TRU elements in SMRs could provide a sustainable and cost-effective alternative to traditional nuclear fuels. Additionally, transmuting TRU elements can mitigate the long-term storage issues associated with spent fuel. This approach not only offers a more sustainable energy source but also addresses concerns

> Unlike traditional plants that use active safety systems requiring electrical signals and human intervention, SMRs' passive systems ensure that cooling continues even if power is lost. This reduces the risk of human error and enhances safety.

related to the scarcity and environmental impact of conventional nuclear energy. Ongoing research into Thorium and TRU fuels for SMRs suggests that they could play a key role in the future of nuclear power [5].

Different Types of SMRs:

SMRs are primarily categorized into land-based and marine-based types. Currently, over 80 SMR designs are being developed or deployed across 18 nuclear member countries, with several significant milestones achieved in their technology.

The marine-based units can be deployed as offshore barge-mounted floating power units or immersible power units. A notable advantage is their ability to be constructed in a factory, assembled in a shipyard, and then transported to remote locations or exported internationally. This flexibility allows them to be sited in off-grid or remote communities, enhancing access to clean energy. Additionally, marine-based SMRs can contribute to decarbonizing industries in marine environments and serve niche markets where land-based nuclear power plants are not feasible or cost-effective. A summary of SMR development as per 2022 data of IAEA is given in Table 1.

Table 1: Current status of the development of SMRs worldwide (Source : 2022 IAEA SMR Booklet [6]).

Reactor type	Present Status
Water-cooled (light water and heavy water) Land-based Reactors	31 designs worldwide, 1- under construction in Argentina
Water-cooled Marine-based Reactors (floating or immersible)	1 (KLT-40S)– operating in Russia, 8 water cooled reactors and 1 molten salt reactor under development and deployment in countries in Asia-Pacific, North America and Europe)
High Temperature Gas Cooled Reactors (HTGR)	14 designs worldwide, 2021 – 1 demo module in China connected to grid
Fast Neutron Reactors (Liquid Metal Fast Reactors, Gas Modular Fast Reactors)	11 designs in various stages of design development, Russia Lead-cooled FNR is under construction (operation plan : by end of 2026)
Molten Salt Reactors	10 designs in licensing process (Canada, USA and UK)
Microreactors (<10 MWe)	6 designs in licensing process (Canada & USA)

The 'Akademik Lomonosov,' (Fig. 1) is a floating power unit in the Russian Federation, features two KLT-40S modules, each with a capacity of 35 MWe. This Pressurized Water Reactor (PWR) type was connected to the grid in December 2019 and commenced commercial operation in May 2020, marking it as the first floating nuclear power plant. This is enough to supply electricity and heat for Pevek, where the population is around 4000. The High Temperature Gas-Cooled Reactor-Pebble-bed Module (HTR-PM) of 210 MWe in China was connected to the grid in December 2021 and reached full power operation at end of 2022. The CAREM25

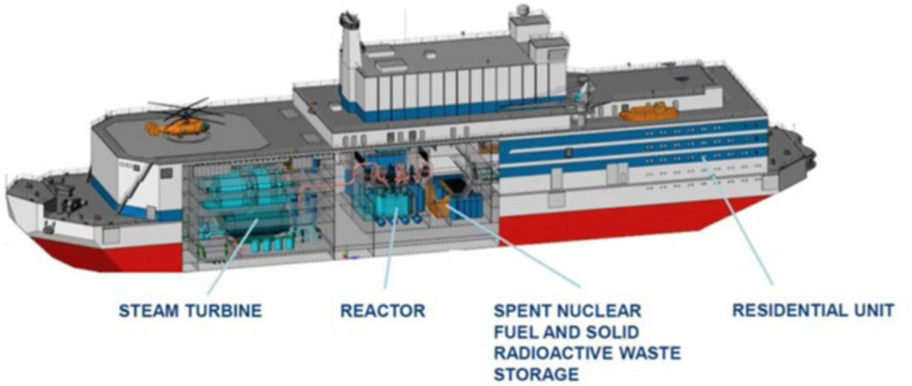

Figure 1: Layout of the floating SMR 'Akademik Lomonosov' (Source : Rosatom)

Figure 2: Power range of Marine-based SMRs (Source : 2023 IAEA Marine-based SMRs booklet [5])

in Argentina is under construction and is expected to reach first criticality in 2026. The construction of ACP100 in China started in July 2021 and is targeted to start commercial operation by the end of 2026. The construction of BREST-OD-300 in Russian Federation began in June 2021 and is planned to be completed in 2026. The NuScale Power Modul in the United States has received Standard Design Approval from U.S. NRC in September 2020. The NRC has directed to issue a final rule that certifies NuScale's SMR design for use in the United States.

Marine-based SMRs are deployed in a diverse range of power outputs, as illustrated in Fig. 2. Major applications of Marine-based SMRs includes the production of hydrogen, ammonia, synthetic fuels for maritime transport and transport fuels; hybrid energy systems; power off-shore platforms; provide power to remote communities; seawater desalination and marine vessel propulsion.

Marine-based SMRs and land-based SMRs have similar technical features, including passive safety systems and design simplicity. Marine-based SMRs are compact for barge installation, use higher uranium enrichment, and have longer refueling cycles (2-12 years). PWR types use a single batch fuel approach, while Molten Salt Reactors refuel every 12 years. Russia is considering to run a centralized service facility for maintenance and refueling. Spent fuel management varies by policy. They may be returned to the supplier state for storage, final disposal, or reprocessing, while with low-activity waste stored on-site and then sent to radioactive waste facilities in the host country for storage or disposal.

Marine-based SMRs must account for external hazards like tsunamis, aircraft crashes, and underwater earthquakes. Unlike land-based reactors, marine SMRs must be designed to handle the effects of ocean waves and swells on their thermal hydraulic systems and control rod performance, especially during tilting. The barge containing the SMRs has multiple protective barriers—nuclear fuel pellets, reactor pressure vessel, reactor compartment, and barge hull—that effectively prevent radiation release and protect both crew members and the surrounding environment.

Conclusion

Considering the primary constraints of introducing nuclear power in Sri Lanka—such as relatively low electricity demand, limited suitable land, waste management challenges, high capital costs, safety concerns, and difficulties integrating a large reactor into the national grid—marine-based Small Modular Reactors (SMRs) could be a more viable option than land-based reactors. However, a thorough investigation of all technical and other relevant aspects is necessary before moving forward.

References:

1. https://www.sciencedirect.com/science/article/abs/pii/S0196890413007516
2. B. Mignacca, G. Locatelli, 'Economics and finance of Small Modular Reactors: A systematic review and research agenda', Renewable and Sustainable Energy Reviews, Vol. 118, 109519 Feb 2020 109519
3. A. Lokhov, R. Cameron and V. Sozonium, 'OECD/NEA Study on the Economics and Market of Smalla Reactros', Nuclear Engineering and Technology, Vol. 45, No. 6, pp 701-706 Nov. 2013
4. https://www.energy.gov/ne/benefits-small-modular-reactors-smrs
5. R. Akbari, M.A. Nasr, F. D'Auria, et al, 'Analysis of thorium-transuranic fuel deployment in a LW-SMR : A solution toward sustainable fuel supply for the future plants', Nuclear Engineering and Design, Vol. 421, 113090, May 2024
6. https://aris.iaea.org
7. https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors

Article by

Thushara Damayanthi

Department of Electrical Engineering, Faculty of Engineering, University of Moratuwa, Sri Lanka